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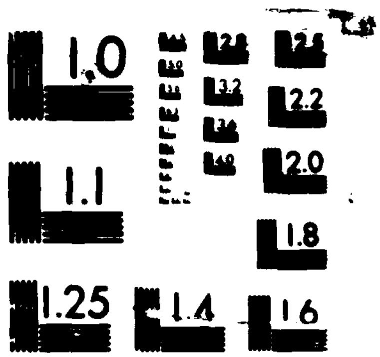

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Laser-Produced Plasmas and Hypervelocity Acceleration

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May 15, 1987

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Laser-produced plasmas have properties that overlap those of armatures required for hypervelocity particle acceleration. This makes them useful as a test bed for advanced acceleration schemes and effects. In addition, sophisticated diagnostics have been developed for measuring laser-produced plasma conditions; many of these techniques can be applied or adapted to KEW armature problems.

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CONTENTS

LASER-PRODUCED PLASMAS AND HYPERVELOCITY ACCELERATION

I. Laser-Produced Plasmas and Plasma Propellants

Plasmas produced by intense laser irradiation of material can span a huge parameter space of density and temperature due to the well controlled flexibility of the laser. In particular, laser-produced plasmas overlap the requirements of propellants and armatures needed for very high speed material acceleration. Laser-plasmas can also directly accelerate material to hypervelocities through ablation or other processes.

The density-temperature plasma parameter space for plasma propellants is plotted in Figure 1. Also indicated on this figure are the iso-pressure contours in the 1-to-100 kbar range and sound speeds from 10-to-200 km/s. For efficient propellant type accelerations, such as encountered in light-gas and electro-thermal guns, the sound speed of the propellant needs to be higher than the final projectile velocity. Rail gun-like plasma armatures are also limited to a similar sound speed condition due to the presence of rail-plasma contact regions. Thus, Fig. 1 indicates the approximate plasma density and temperature needed to accelerate material to some final velocity, given the applied pressure. For example, to accelerate material up to 100 km/s then one needs a plasma temperature of over 60 eV and density about 0.1 mg/cc (for hydrogen). Additionally, in Fig. 1 approximate boundaries are drawn which separate different plasma coupling regimes (for hydrogen plasma).[1] Proceeding from high-to-low temperatures, the plasma goes from collisionless to collisional conditions when collision mean-free-paths become shorter than the system size (taken to be 1-cm here). At lower temperatures, but high density, the plasma interatomic electric forces dominate over thermal forces and the plasma is termed strong-coupled; strong-coupled plasmas have less than one particle per Debye sphere. Weakly ionized plasma interactions became important at lower density, when the electron-atom collision frequency is over

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ten-percent of the electron-ion collision frequency. At very high density and low temperature (thermal energy less than the Fermi energy), the electrons obey Fermi-Dirac statistics and the plasma is termed degenerate. Plasma processes in each of these regimes are fundamentally different. It is interesting to note that little is known about strong-coupled plasmas and, although they occupy a central region of parameter space for hypervelocity acceleration, few experiments have been fielded to determine their properties. Thermal and electrical condictivities in the strong-coupled regime are different from those obtained from those assuming an collisional plasma;[2] this in turn may alter hypervelocity system design considerations.

Plasma parameters produced by laser irradiation of solid material fall below the horizontal dashed lines in Fig. 1, in the shaded region, for several common types of lasers. One notes an almost complete overlap of plasma propellant conditions by using Nd-glass laser produced plasmas.

In the next Section, it is shown that near solid-density material has already been accelerated to over 150 km/s using Nd-glass-laser-plasmas. Although the efficiency of such acceleration is too small to be of interest for many applications(< 15%), many lethality and hypervelocity acceleration issues could be addressed. Laser-plasma diagnostic techniques and methods, which are highly developed, would be useful for understanding processes in these plasmas; some of these diagnostics will be described in a following Section. Finally, some advantages of using laser-plasmas to model high-speed acceleration processes will be mentioned.

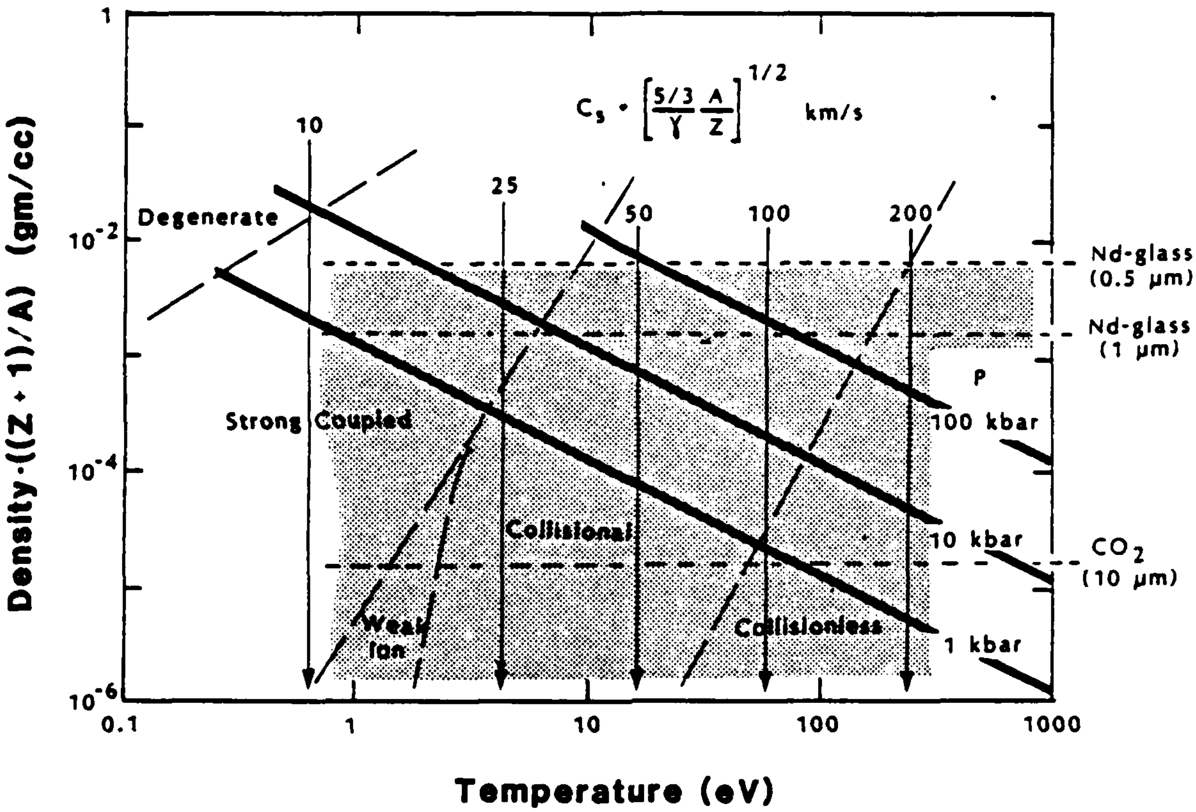

Fig. 1. Pressures and sound speeds as a function of plasma mass density and temperature. Sound speeds are expressed in terms of fully ionized (Z=1) hydrogen (A=1) with a ratio of specific heats, $\gamma = 5/3$. In addition approximate boundaries between collisionless, collisional, strong-coupled, weakly-ionized, and degenerate plasmas are shown as long dashed lines. The area below the horizontal lines are accessible to laser-produced plasmas. Virtually all plasma propellant territory can be attained with Nd-glass lasers operating at either the fundamental wavelength (1-micron), or frequency-doubled (0.5-micron). Carbon-dioxide lasers do not appear well suited for this problem.

II. Direct-Acceleration to 160-km/s.

Thin-foils (10 microns) of aluminium and plastic have been accelerated to speeds beyond 100-km/s by irradiating the rear of the material with a focused, 3-ns, Nd-laser beam,[3,4] as illustrated in Figure 2. In these cases, the laser light ablates some material from the foil, heats it up to several hundred eV, and creates pressures over 1-Mbar; the target accelerates in a rocket-like fashion in reaction to the ablating material. (We are in the upper-right corner of the shaded region of Fig. 1.) Although this type of acceleration has not been optimized for applications other than inertial fusion to date, it

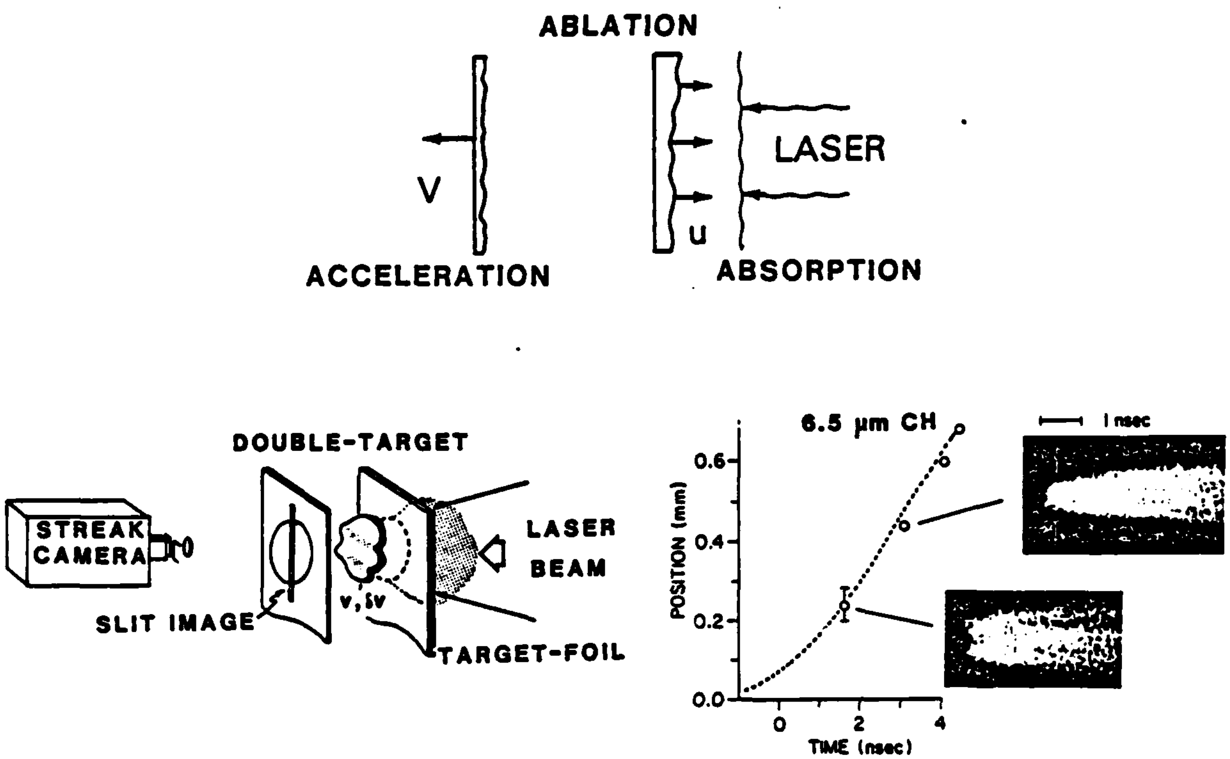

Fig. 2 Geometry for direct laser-ablative acceleration of material to high speeds (top). The laser light is absorbed near the rear of the projectile causing plasma to be ablated and accelerated away from the target; the solid target then accelerates away from the laser in rocket-like reaction to the ablated plasma. The figure at the bottom shows data from a target accelerated to 160 km/s obtained from a double-target, or flyer-plate method (illustrated on the left.

has held the world's velocity record for material accelerated in the laboratory for six years,[5] and is well beyond SDI's speed requirements. The accelerated material motion has been diagnosed in many ways, including; x-radiography, double-target time-of-flight, and particle detectors.[3,6] We know the accelerated material temperature as function of time by using blackbody emissivity[7] and a half-target edge expansion methods.[8] The hydrodynamic stability and uniformity is also fully measured. The ablating plasma (propellant) is likewise well-diagnosed. The plasma density, temperature, and flow pattern are all accurately measured using sophisticated diagnostics developed primarily in support of the national inertial confinement fusion program. This is dispite the fact that these plasmas are extremely dense, hot, and dynamic (ns time scales). Many of the diagnostics methods, or their analogs, could be used in hypervelocity projectile applications.

III. Diagnostics for Dense, Hot Laser-Plasmas.

Laser-produced plasmas and hypervelocity propellants share a number of diagnostic challanges. Both classes of plasmas are dense, highly ionized, hot, and dynamic.

Spectroscopy, line and continuum, gives density, species, ionization state, and temperature information. Zeeman split lines have allowed internal magnetic-field strength measurements.[9]

Laser scattering, shadowgraphy, and interferometry give density, temperature, and plasma structure and turbulence information. Faraday rotation measurements of laser probe light give magnetic field strengths and orientation.[10]

One class of diagnostics particularly well suited to a number of armature problems, which also was invented for laser-produced plasmas, is the tracer-dot technique.[11] The basic idea here is to imbed small dots of some emissive material in the bulk plasma, as illustrated in Figure 3. These tracer regions then map out the hydrodynamic patterns of the flow in a manner analogous to dye streamers in fluid experiments. One looks for the characteristic radiation of the tracer material (eg., x rays for hot (keV) plasmas, XUV for warm (tens-of-eV) plasma, etc.). Alternatively, one could look for the absorption of backlighting radiation in the tracer material. Turbulence or abnormal flow patterns are immediately visualized. This technique becomes even more powerful when combined with spectroscopy.[12] Spatially localized density, temperature, and flow velocity measurements are possible, eventhough deep within the bulk plasma. Critical opacity measurements are also facilitated.[13]

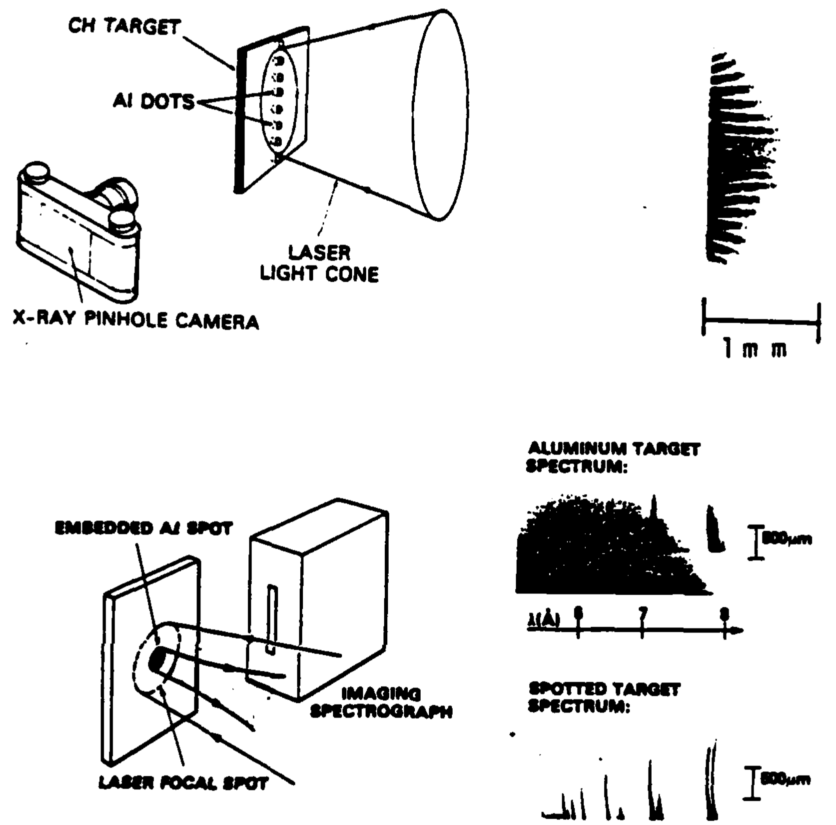

Fig. 3 Tracer-dot diagnostics techniques enable flow visualization, density and temperature measurements, and measurments of other parameters. The figure at the top left shows the geometry; at the top right is an example of hydrodynamic flow visualization, while the figure on the bottom shows the setup for localized spectroscopy and sample spectra from a solid Al target and from a tracer-dot implant target. Note the improved spectral resolution with the tracer-dot target.

IV. Laser-Plasmas as Hypervelocity Accelerator Test-beds.

It is unlikely that laser-acceleration of material can make an attractive kinetic energy device; it is just too inefficient a process. But, laser-plasmas can access most advanced propellant conditions, and they have been demonstrated to be capable of direct hypervelocity material acceleration to speeds above 150 km/s. Moreover, laser-produced plasmas are very reproducible, experiments can be performed many times a day without destroying the apparatus, they can be reconfigured easily to test new geometries, and good diagnostics abound. In addition to producing propellant-like ablation plasmas by direct laser irradiation, lasers can also explosively heat thin films[14] to access the very high-density low-temperature regime. Hypervelocity acceleration concepts can be tried, erosion and heat transfer characteristics of materials can be measured under propellant-like conditions. and the reaction of micro-projectiles to high accelerations and armature-like plasmas can be measured.

Armatures often carry high currents and magnetic fields to propel the projectile. Again it is emphasized that little is known about thermal and electrical conductivities in the strong-coupled regime. Similiar conditions could be imposed upon laser-plasmas by external electrodes and magnets. Current filamentation, arcing, Rayleigh-Taylor instability, and other processes occuring within the armature plasma could then be observed, if present.[15]
Alternately, diagnostic techniques already developed for dense dynamic laser-plasmas can be adapted to actual launcher experiments to elucidate the many uncertainties. For example, tracer materials can be implanted in EM-launcher rails, barrel, or (originally solid) armatures, to determine erosion rates, heat-transfer coefficients, flow patterns, and so on.

V. Summary.

Laser-produced plasmas appear useful as test-beds for advanced high-velocity acceleration schemes. Also, many diagnostics developed for laser-produced plasmas could be adapted for EM-launcher/propellant applications.

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